DELAMINATION OF C-SI MODULE ENCAPSULATION: INSIGHT INTO CAUSES AND LONG-TERM EFFECTS

Andrew Fairbrother[1], Luca Gnocchi[1], Alessandro Virtuani[1], Christophe Ballif[1,2]
1 – École Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Photovoltaics and Thin-Film Electronics Laboratory, Rue de la Maladière 71b, 2002 Neuchâtel (Switzerland)
2 – CSEM PV-Center, Rue de Jaquet-Droz 1, 2002 Neuchâtel (Switzerland)

ABSTRACT: The encapsulation of photovoltaic (PV) modules insulates solar cells and internal electrical components, and protects them from environmental stresses. Encapsulant delamination is a common mode of failure, and can appear immediately after manufacturing (quality issues) or it can occur over time (degradation). In both cases, the long-term impact of delamination on module performance is poorly quantified. In this work the causes and effects of delamination were examined in greater detail. Inhomogeneities during lamination (e.g. temperature, uncured material composition) form areas with different properties which are expected to be more susceptible to delamination over time. To assess the long-term effect of delamination on performance, single cell c-Si modules with an ethylene-vinyl acetate (EVA) encapsulant and poor lamination quality or selective delamination were manufactured and subjected to a series of accelerated weathering tests (damp heat (DH), thermal cycling (TC), ultraviolet (UV) light). The extent of delamination increased over time, and lead to a higher rate of performance-loss compared to reference modules, for example, more than double in the case of damp heat exposure.
Keywords: EVA, encapsulation, delamination, quality, reliability

1 INTRODUCTION

Encapsulants are arguably the most critical component of the packaging system of a photovoltaic (PV) module. These polymeric materials are in direct contact with the solar cells and internal circuit, and must provide adequate insulation, environmental protection, and adhesion to other module layers over the lifetime of the module. Major degradation and failure modes of PV modules are either caused directly by the encapsulant itself (e.g. delamination, discoloration)[1]–[4] or mediated by it (e.g. corrosion, potential induced degradation (PID), backsheet cracking).[5]–[7] Of these, encapsulant delamination is one of the most common failure modes of PV module packaging.[8]–[11] Voids or delamination can appear during or immediately after manufacturing, or develop over time. In spite of the prevalent nature of encapsulant delamination, factors favoring formation of this defect are poorly understood.[12]–[14] Moreover, the long-term impact of delamination on module performance is poorly defined, though it is expected to accelerate corrosion of solar cell metallization and wiring.[2], [15], [16]

Lamination quality is an important metric in module manufacturing, and numerous tools have been developed to quantify it for quality control purposes.[17]–[22] Poorly optimized or controlled lamination procedures can lead to void formation or delamination, for example, due to process (e.g. temperature, pressure) or material non-uniformities, insufficient encapsulation material to laminate a module, or volatile compounds which are not effectively removed from the module stack.[10], [12], [23] Over time, delamination can also occur as a result of degradation. As the different module layers degrade, the interfaces between them deteriorate from accumulation of degradation products. This reduces the adhesion strength, and in conjunction with (thermo)mechanical stresses, delaminated areas can eventually form.[13], [14], [24]

In spite of the prevalence of encapsulant delamination, its effect on performance is not well understood. Two immediate effects are known, first, the additional interface affects the heat transfer characteristics of a module and can lead to higher operating temperatures. Second, when the delaminated areas appear above a solar cell they form an additional interface where light scattering reduces total irradiance at the solar cell.[2], [16] Beyond these instantaneous two effects, it is expected that delaminated areas act as condensation points for moisture and acetic acid within a module. These areas would then experience accelerated corrosion of solar cell metallization and interconnects.[2], [15], [16] However, no detailed quantification of this type of effect has been made to assess its severity.

In that context, this work explored some of the causes and effects of encapsulant delamination in PV modules with an ethylene-vinyl acetate (EVA) encapsulant. First, it profiled factors that can lead to poor or inhomogeneous lamination quality, including temperature and uncured material composition. And second, it assessed the impact of low quality lamination and selective delamination on module performance in accelerated laboratory weathering tests. These results present a cradle-to-grave (from manufacturing to end-of-life) perspective on the importance of module packaging quality, and are a first quantification of the latent and long-term effect that delamination has on module lifetime.

2 EXPERIMENTAL

2.1 Factors affecting lamination quality

The first part of this study comprised an analysis of aspects affecting lamination quality. Lamination parameters have a strong impact on the chemical and mechanical properties of encapsulants, including gel content and adhesion strength.[3], [17]–[23] Homogeneity is an important process control factor, so two aspects were examined: 1) laminator temperature and 2) uncured material EVA encapsulant composition. Laminator temperature (Swiss Solar Systems (3S) Laminator S1815) was measured with a series of thermocouples near the edges of the 140 cm x 190 cm laminator plates at 140°C, a common lamination temperature for EVA.

Encapsulant composition was modified before module lamination by storing in different humidity conditions, principally to alter its moisture content. This included storage under typically recommended manufacturer conditions (e.g. <25°C and <50% relative humidity (RH)), and extremely damp conditions (20°C and 100% RH). Single cell (c-Si, Al-BSF) modules were laminated with the reference EVA and "damp" EVA.

2.2 Selectively induced encapsulant delamination

The second part of the work examined selective delamination and its impact on module performance. Single cell modules were fabricated with the following bill of materials, shown schematically in Figure 1a: 1) glass, 2) EVA, 3) ethylene tetrafluoroethylene (ETFE), 4) solar cell (c-Si, Al-BSF), 5) EVA, 6) polyethylene terephthalate (PET)/PET/EVA backsheet. ETFE has low adhesion, and was placed over the entire cell or ribbon interconnects (Figure 1b). This formed a weak interface which readily delaminated.[25] Reference modules without ETFE were also prepared.

2.3 Module weathering tests

Single cell modules with poor lamination quality and intentional delamination were subjected to accelerated and outdoor weathering tests, detailed in Table I. These included damp heat, thermal cycling, ultraviolet (UV) light, and outdoor exposure. The test time and status is also shown in the Table, some of which are still in progress or not yet started for each module type at the time of publication. For each weathering test, modules were periodically characterized by visual inspection, AM1.5 light current-voltage (I-V) characteristics, and electroluminescence (EL) at Impp.

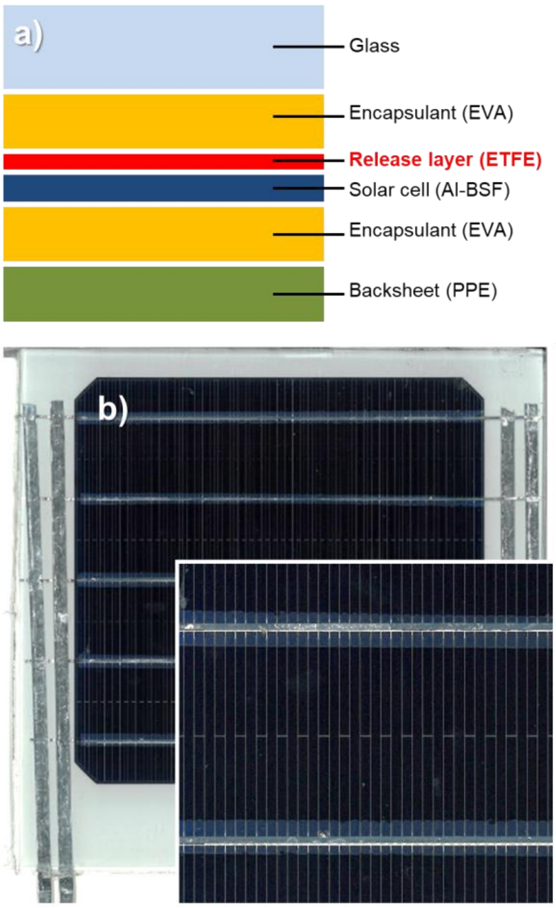

Figure 1. Module structure (a), including ETFE to facilitate selective delamination across the entire cell or along interconnects (b) (inset is a closer image of two ribbon interconnects with intentional encapsulant delamination).

Table I. Weathering test conditions for modules.

Test	Conditions	Status
Damp heat	85°C and 85% RH	Completed (4000 hours)
Thermal cycling	-40°C to 85°C	In progress (400 cycles)
UV light	Xenon arc (0.8 W m^{-2} (@340 nm), 65°C/90°C (T_{Ch}/T_{BP}), 20% RH	In progress (3000 hours)
Outdoor	Open-rack mount in Neuchâtel, Switzerland	Not started

3 RESULTS AND DISCUSSION

3.1 Factors affecting lamination quality

For the laminator in this work temperature was monitored by the system with seven temperature sensors, which tended to be within ±2°C of the set temperature and each other. Temperature measurements with higher spatial resolution were needed to identify more localized deviations in temperature. The laminator plates had an overall dimension of 140 cm x 190 cm, and a temperature profile from 65 cm to the edge of the plates is shown in Figure 2 for a set temperature of 140°C. The temperature dropped slightly (≈135°C) about 30 cm from the edge, and then rapidly within 10 cm from the edge (down to 113°C). In this border region (0-30 cm from edge) there was significant variability of up to ±8°C for a given distance, while closer to the center of the plates variability was up to ±3°C.

Large differences in curing temperature of EVA can lead to very different properties.[17], [18], [20] During module manufacturing regions of high variability, e.g. along the plate edges, are not used. Regardless, this presents a large "dead-space" within a laminator that is not actually useable, and increases its footprint on the factory floor. Additionally, if heating elements malfunction, a large variation in temperature can occur closer to the center of the laminator.

Storage conditions of uncured polymeric materials can have a strong influence on composition because of moisture absorption and the volatile nature of additives for processing and stabilization.[23] Figure 3 shows visual inspection of modules laminated with EVA under ideal storage conditions, and high humidity conditions (before and after 250 hours of UV exposure). The module with properly stored EVA exhibited a clear aspect, with

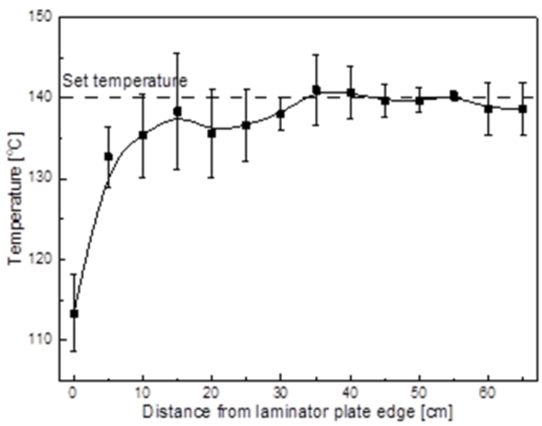

Figure 2. Laminator temperature profile near the edge of plates, with set temperature of 140°C.

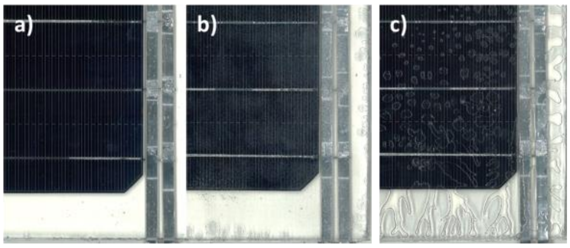

Figure 3. Visual inspection of module lamination quality with EVA stored under manufacturer recommended conditions (a), and 100% RH conditions before (b) and after just 250 hours of UV exposure (c).

no visually apparent defects. The module with improperly conditioned EVA had a milky appearance across the solar cell, in addition to bubbles and delamination at the edges of the module. After just 250 hours of UV exposure (approximately equivalent to a few months in a mid-latitude location), delaminated regions appeared across the entire module surface.

After 3000 hours of UV exposure there was no significant difference module performance, in spite of the widespread delamination observed in the module prepared with the damp EVA. While this may appear remarkable, 3000 hours is only approximately equivalent to three years of outdoor UV exposure, and therefore the long-term effect that lamination quality has on module performance still eludes in this test.

3.2 Selectively induced encapsulant delamination

Intentionally induced delamination was accomplished by insertion of a low-adhesion ETFE layer between the top layer EVA and solar cells. Accelerated weathering under damp heat showed a higher rate of degradation for greater extent of delamination, seen in Figure 4a.

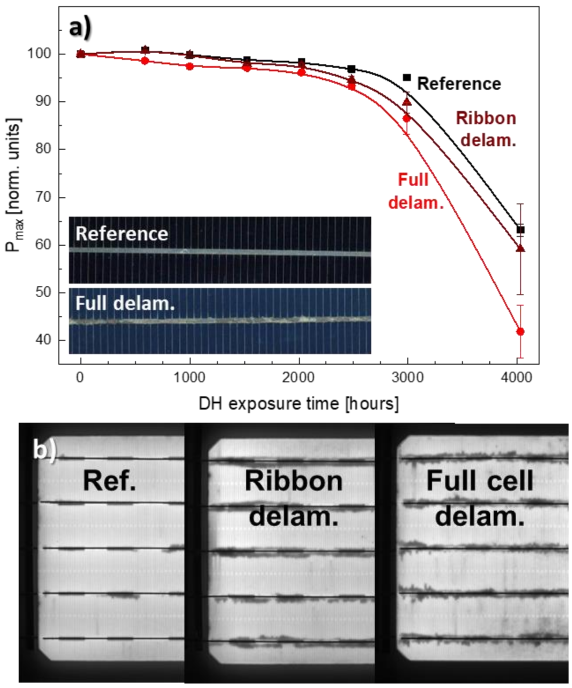

Figure 4. Selectively delaminated modules during damp heat exposure, including normalized power-loss (a) and electroluminescence images after 2500 hours (b). Inset of (a) shows close ups of interconnect ribbons after 2500 hours exposure.

Modules with the full-cell delamination had experienced power-loss at more than double the rate of the non-delaminated reference cells up to 3000 hours. After 4000 hours, retained maximum power was 41.9%±5.6% for the delaminated modules, compared to 63.2%±1.3% for the reference modules. Visual inspection (inset Figure 4a) showed evidence of corrosion along the ribbon wiring for delaminated modules. The effect of this corrosion becomes clear in EL images taken after 2500 hours exposure (Figure 4b), which indicated greater loss of current generation along the ribbon wiring for the delaminated specimens.

Thermal cycling was completed up to 400 cycles, and UV exposure up to 3000 hours. Up to this time, there was a small, but not statistically significant difference in the electrical characteristics between modules. In spite of this, these tests, in addition to outdoor exposure, are ongoing because delamination is expected to have a delayed response on module performance.

4 CONCLUSIONS

Weathering tests of modules with poor lamination quality of intentional delamination have been made to uncover their impact on module performance. Some tests (thermal cycling, UV) have not yet shown that it has a major influence, though they are still ongoing because any effects are expected to be delayed. Damp heat testing, however, showed that the rate of power-loss for a fully delaminated modules was more than double that of non-delaminated reference modules up to 3000 hours. Whole cell delamination is an extreme case, but even for smaller delaminated areas (e.g. along interconnects) the rate of performance-loss was higher than reference modules. Under real-world operating conditions over >25 years, the financial losses from this reduced performance would be significant. Process control, specifically laminator temperature uniformity and uncured encapsulant water content, was shown to have a major impact on encapsulant properties. Module packaging plays a crucial role in the safe and reliable operation of PV modules for their intended lifetime, thus greater understanding of the causes of delamination and its subsequent effects is necessary to improve product design and processing.

5 ACKNOWLEDGEMENTS

Authors thank the European Commission for financial support in the framework of the H2020 Be-Smart project (grant Agreement #818009).

6 REFERENCES

[1] F. J. Pern, “Ethylene-vinyl acetate (EVA) encapsulants for photovoltaic modules: Degradation and discoloration mechanisms and formulation modifications for improved photostability,” Angew. Makromol. Chem., vol. 252, no. 1, pp. 195–216, 1997, doi: 10.1002/apmc.1997.052520114.

[2] N. C. Park, J. S. Jeong, B. J. Kang, and D. H. Kim, “The effect of encapsulant discoloration and delamination on the electrical characteristics of photovoltaic module,” Microelectron. Reliab., vol. 53, no. 9–11, pp. 1818–1822, Sep. 2013, doi: 10.1016/j.microrel.2013.07.062.

[3] G. Oreski and G. M. Wallner, “Evaluation of the

aging behavior of ethylene copolymer films for solar applications under accelerated weathering conditions," Sol. Energy, vol. 83, no. 7, pp. 1040–1047, Jul. 2009, doi: 10.1016/j.solener.2009.01.009.

[4] G. Oreski et al., "Properties and degradation behaviour of polyolefin encapsulants for photovoltaic modules," Prog. Photovolt. Res. Appl., p. pip.3323, Aug. 2020, doi: 10.1002/pip.3323.

[5] A. Virtuani, E. Annigoni, and C. Ballif, "One-type-fits-all-systems: Strategies for preventing potential-induced degradation in crystalline silicon solar photovoltaic modules," Prog. Photovolt. Res. Appl., vol. 27, no. 1, pp. 13–21, Jan. 2019, doi: 10.1002/pip.3066.

[6] Y. Lyu et al., "Drivers for the cracking of multilayer polyamide-based backsheets in field photovoltaic modules: In-depth degradation mapping analysis," Prog. Photovolt. Res. Appl., vol. 28, no. 7, pp. 704–716, 2020, doi: 10.1002/pip.3260.

[7] M. D. Kempe, G. J. Jorgensen, K. M. Terwilliger, T. J. McMahon, C. E. Kennedy, and T. T. Borek, "Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices," Sol. Energy Mater. Sol. Cells, vol. 91, no. 4, pp. 315–329, Feb. 2007, doi: 10.1016/j.solmat.2006.10.009.

[8] M. Köntges, S. Kurtz, C. Packard, U. Jahn, K. A. Berger, and K. Kato, "Performance and reliability of photovoltaic systems: subtask 3.2: Review of failures of photovoltaic modules: IEA PVPS task 13: external final report IEA-PVPS," International Energy Agency, Photovoltaic Power Systems Programme, Sankt Ursen, 2014.

[9] C. E. Chamberlin, M. A. Rocheleau, M. W. Marshall, A. M. Reis, N. T. Coleman, and P. A. Lehman, "Comparison of PV module performance before and after 11 and 20 years of field exposure," in 37th IEEE Photovoltaic Specialists Conference (PVSC), Seattle, WA, USA, 2011, pp. 000101–000105, doi: 10.1109/PVSC.2011.6185854.

[10] J. H. Wohlgemuth, P. Hacke, N. Bosco, D. C. Miller, M. D. Kempe, and S. R. Kurtz, "Assessing the causes of encapsulant delamination in PV modules," in 43rd IEEE Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 2016, pp. 0248–0254, doi: 10.1109/PVSC.2016.7749589.

[11] T. J. Trout et al., "PV Module Durability – connecting field results, accelerated testing, and materials," in 44th IEEE Photovoltaic Specialist Conference (PVSC), Washington, DC, USA, 2017, pp. 2312–2317.

[12] H.-Y. Li, Y. Luo, C. Ballif, and L.-E. Perret-Aebi, "Modeling of Voids Evolution in the Encapsulation Process of Photovoltaic Modules," Polym. Polym. Compos., vol. 23, no. 6, pp. 375–388, Jul. 2015, doi: 10.1177/096739111502300603.

[13] J. Tracy, N. Bosco, and R. Dauskardt, "Encapsulant Adhesion to Surface Metallization on Photovoltaic Cells," IEEE J. Photovolt., vol. 7, no. 6, pp. 1635–1639, Nov. 2017, doi: 10.1109/JPHOTOV.2017.2746572.

[14] F. D. Novoa, D. C. Miller, and R. H. Dauskardt, "Adhesion and debonding kinetics of photovoltaic encapsulation in moist environments: Adhesion and debonding kinetics of photovoltaic encapsulation," Prog. Photovolt. Res. Appl., vol. 24, no. 2, pp. 183–194, Feb. 2016, doi: 10.1002/pip.2657.

[15] E. E. van Dyk, J. B. Chamel, and A. R. Gxasheka, "Investigation of delamination in an edge-defined film-fed growth photovoltaic module," Sol. Energy Mater. Sol. Cells, vol. 88, no. 4, pp. 403–411, Sep. 2005, doi: 10.1016/j.solmat.2004.12.004.

[16] M. A. Quintana, D. L. King, T. J. McMahon, and C. R. Osterwald, "Commonly observed degradation in field-aged photovoltaic modules," in 29th IEEE Photovoltaics Specialist Conference (PVSC), New Orleans, LA, USA, 2002, pp. 1436–1439, doi: 10.1109/PVSC.2002.1190879.

[17] H.-Y. Li, Y. Luo, C. Ballif, and L.-E. Perret-Aebi, "Fast and Nondestructive Detection on the EVA Gel Content in Photovoltaic Modules by Optical Reflection," IEEE J. Photovolt., vol. 5, no. 3, pp. 759–765, May 2015, doi: 10.1109/JPHOTOV.2015.2397603.

[18] H.-Y. Li, L.-E. Perret-Aebi, R. Théron, C. Ballif, Y. Luo, and R. F. M. Lange, "Optical transmission as a fast and non-destructive tool for determination of ethylene-co-vinyl acetate curing state in photovoltaic modules," Prog. Photovolt. Res. Appl., vol. 21, no. 2, pp. 187–194, 2013, doi: 10.1002/pip.1175.

[19] Ch. Hirschl et al., "In-line determination of the degree of crosslinking of ethylene vinyl acetate in PV modules by Raman spectroscopy," Sol. Energy Mater. Sol. Cells, vol. 152, pp. 10–20, Aug. 2016, doi: 10.1016/j.solmat.2016.03.019.

[20] Ch. Hirschl et al., "Determining the degree of crosslinking of ethylene vinyl acetate photovoltaic module encapsulants—A comparative study," Sol. Energy Mater. Sol. Cells, vol. 116, pp. 203–218, Sep. 2013, doi: 10.1016/j.solmat.2013.04.022.

[21] C. Peike, W. Phondongnok, T. Kaltenbach, K.-A. Weiss, and M. Koehl, "Non-destructive determination of the cross-linking degree of EVA by Raman Spectroscopy," Open J. Renew. Energy Sustain. Dev., vol. 2014, no. 1, pp. 14–21, Mar. 2014, doi: 10.15764/RESD.2014.01002.

[22] G. Oreski, A. Rauschenbach, C. Hirschl, M. Kraft, G. C. Eder, and G. Pinter, "Crosslinking and post-crosslinking of ethylene vinyl acetate in photovoltaic modules," J. Appl. Polym. Sci., vol. 134, no. 23, Jun. 2017, doi: 10.1002/app.44912.

[23] T. Shioda, "Short-term and long-term field experiences in Japan in terms of PV encapsulant," presented at the 4th Atlas/NIST Workshop on Photovoltaic Materials Durability, Gaithersburg, MD, USA, 2017.

[24] N. Bosco, S. Moffitt, and L. T. Schelhas, "Mechanisms of adhesion degradation at the photovoltiac module's cell metallization-encapsulant interface," Prog. Photovolt. Res. Appl., vol. 27, no. 4, pp. 340–345, Apr. 2019, doi: 10.1002/pip.3106.

[25] L. Gnocchi, A. Virtuani, A. Vallat-Michel, A. Fairbrother, H.-Y. Li, and C. Ballif, "Measuring and Modelling the Generation of Acetic Acid in Aged Ethylene-Vinyl Acetate-Based Encapsulants Used in Solar Modules," 36th Eur. Photovolt. Sol. Energy Conf. Exhib., pp. 1069–1072, Oct. 2019, doi: 10.4229/EUPVSEC20192019-4AV.1.34.